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**Session 4pMU: Measurements, Modeling, and Simulations of Brass Instruments**

## **4pMU10. The soft-source impedance of the lip-reed: Experimental measurements with an artificial mouth**

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Most theoretical descriptions of the brass instrument lip-reed consider the acoustical condition at the lips to be a closed, rigid termination, corresponding to a unitary reflectance. This assumption is carried through to many computational models as well. In reality, the protrusion of the player's lips into the mouthpiece causes a periodic shortening/extension of the acoustical tube downstream, an effect sometimes but not always incorporated into such models. Of interest here is the absorption properties of the lip termination, the so-called 'soft source impedance'. This provides a further modification to the boundary condition at the lips, since the soft, deformable nature of the lips are likely to cause some extra damping of the acoustic standing wave. Measurements are presented to demonstrate this damping effect using an artificial mouth. This is achieved through measurements of the lip reflectance from downstream of the lips, from where it is shown that the reflectance shows a dip at the peak absorbance frequency of the lips. The frequency of the absorbance is shown to vary as the lip parameters are changed.

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## INTRODUCTION

In brass instrument acoustics it is usually assumed that the acoustical condition at the plane of the player's lips is 'closed' and perfectly reflective. This leads to the common description of the brass instrument family as having an acoustical pressure anti-node at the lips and a node at the end of the bell. Depending on the profile of the bore, whether conical, cylindrical, exponentially-flaring and so on, it is possible to estimate the acoustical resonance properties the instrument from first principals.

In normal situations the playing frequency of the instrument is expected to be strongly affected by the absolute and relative frequencies of the resonances. The fact that these simple theoretical analyses match up rather well with measurements of an instrument's input impedance suggests that the closed-mouthpiece, open-bell assumption is quite reasonable. However, such results are perhaps not surprising given that most practical input impedance measurements require a rigid, (near) perfectly reflecting plane at the input mouthpiece end, which is the very condition used for the theoretical descriptions.

The input impedance is defined as the ratio of acoustic pressure to acoustic volume velocity through a plane. In brass instrument this plane is usually taken to be at the input to the mouthpiece. It is normally assumed that the source plane is perfectly reflective to acoustic waves, so that a travelling wave heading towards the mouthpiece from the instrument will be perfectly reflected with no loss of energy, a so-called 'unitary reflectance' condition. The extent to which this is a reasonable assumption when the terminating surface is a player's lips is the subject of this paper.

A number of practical tools are now available for measuring the input impedance of an acoustical bore. These include the classic capillary-source methods[1], multiple microphone measurements using acoustic pulse reflectometry[2] and commercial tools such as BIAS[3], which is related to the capillary-source method. In general all share the common assumption of perfect acoustic reflectance at the mouthpiece/lip plane.

In most computational treatments of the lip-reed a broadly similar acoustical condition at the lips is assumed. Whether the model is the classic one-mass 'outward striking' model as originally proposed by Helmholtz[4], a one or two-mass transverse 'inward striking' model[5] as originally proposed for the vocal folds[6], or the elegant one-mass, two degree of freedom model of Adachi & Sato[7, 8], the usual assumption is that acoustical waves incident onto the lips will perfectly reflect back up into the instrument bore with no energy loss.

There are however two issues that seem relevant when considering in more detail the condition at the lips. Firstly, the lips oscillate during playing, both transversely and longitudinally into/out of the mouthpiece, so that the actual acoustical condition at the mouthpiece end of the instrument varies continuously between open/closed and slightly longer/shorter effective length. Secondly, the lips themselves are somewhat soft and deformable and so are clearly not perfectly rigid, even when fully closed.

The first of these issues is at least partially addressed with input impedance measurement setups such as BIAS. Here it is possible to represent the volume occupied in the mouthpiece by the lips through use of a small rubber gasket that protrudes into the mouthpiece. This alters the effective length of the instrument, which can be critical for observing appropriately tuned resonances. However, the physical properties of such a protrusion are likely to be rather different to those of real human lip tissue, so the true energy absorbance characteristics of the lips will not be taken into account in producing the input impedance measurement. Reducing the volume of the mouthpiece like this is also somewhat ad hoc, and does not necessarily match exactly what a player would do. Indeed, it is to be expected that different players with differently shaped lips are likely to adopt different strategies for 'tuning' their instrument. Thus in many cases it seems sensible to use the basic flat plate mouthpiece condition for

measurements of input impedance with rigs like BIAS.

The motion of the lips into/out of the mouthpiece is usually at least partially incorporated into computational models through the inclusion of an extra volume source term due to the displacement of the lips. However, the acoustical absorbance properties of the lips are not generally included in the model.

There is also a further consideration that relates to both of the aforementioned issues, which is the treatment of the lips during closure. Nearly all lumped-element lip-reed models necessarily impose a change of lip parameters when collision between the lips occurs during a simulation. There are various approaches, but they mostly share in common that the lip stiffness is suddenly increased to around three times the rest value[8]. A fuller description of the acoustical condition at the lips may help to inform a more refined description for such models.

Recently Kemp and Smith[9] considered the ‘true’ acoustical condition at the lips, taking into account some of the aforementioned effects. A ‘soft source impedance’ was defined that depended upon the pressure that would be measured at a source plane of acoustic volume velocity that differs from a flat, perfectly reflecting plate. Initial measurements on a human player led to marked alterations in the (soft source) input impedance curves that were well within the playing range. In this paper the work is carried forward to include systematic measurements with an artificial mouth.

## OBJECTIVES AND BACKGROUND

### Objectives of the study

The purpose of this paper is to systematically measure the acoustical reflectance properties of a pair of *in vitro* artificial lips when configured in a playable condition. The aim is to try to quantify the variation of the acoustical reflectance function of the artificial lip-reed with the physically-controllable lip parameters, and to compare this to the idealised perfect reflectance normally assumed in computational models of the lip-reed.

In section 2.2 a brief overview of impedance and soft-source impedance is presented. The acoustical measurement technique used in this work, wave separation by acoustic pulse reflectometry, is then described in section 3.1. The *in vitro* lip-reed model is briefly described in section 3.2. The acoustical reflectance results are finally presented in section 4.1.

### Acoustic reflectance and the soft source impedance

#### Input impedance under unitary source reflectance

For an oscillating column of air, the acoustic input impedance is defined in the frequency domain as[10]

$$Z_{in}(\omega) = \frac{P(\omega)}{U(\omega)} \quad (1)$$

where  $P(\omega)$  is the pressure and  $U(\omega)$  is the volume velocity, both at the input plane of the instrument, and  $\omega$  is angular frequency. The input impedance is determined by the physical characteristics of the instrument such as its length and bore profile, and can be useful in characterising an instrument’s tonal qualities.

The acoustic reflectance, or reflection function[10], is normally defined as

$$R(\omega) = \frac{Z_{in}(\omega) - Z_c}{Z_{in}(\omega) + Z_c} \quad (2)$$

where  $Z_c$  is the characteristic impedance of the instrument, defined as  $\rho c/S_{cup}$  where  $\rho$  is the density of air,  $c$  is the speed of sound in air and  $S_{cup}$  is the cross sectional area of the mouthpiece cup at the input plane to the instrument. This function shows how frequencies in a sound wave are reflected as they travel along the bore profile. However, it does not take into account how the waves are reflected when they return to the input end of the instrument, and whether or not they lose any energy during reflection, as the input impedance calculation assumes that the input is a flat, perfectly reflecting source.

### Non-unitary reflectance of the lips and the soft source impedance

Kemp and Smith[9] showed that by including a non-unitary reflection term that corresponds to the reflection characteristics of the input of the instrument,  $V(\omega)$ , a soft source can be modelled. By using this soft source term as well as the reflection function calculated using the input impedance, the pressure wave from a forward travelling impulse at the input is:

$$\begin{aligned} P_{\delta}^{+}(\omega) &= 1 + V(\omega)R(\omega) + (V(\omega)R(\omega))^2 + \dots \\ &= \frac{1}{1 - V(\omega)R(\omega)} \end{aligned} \quad (3)$$

$$\begin{aligned} P_{\delta}^{-}(\omega) &= R(\omega) + V(\omega)(R(\omega))^2 + (V(\omega))^2(R(\omega))^3 + \dots \\ &= \frac{R(\omega)}{1 - V(\omega)R(\omega)} \end{aligned} \quad (4)$$

where the + superscript denotes the forward going component, and the – superscript the backwards going component.

The total pressure is then

$$P_{\delta}(\omega) = P_{\delta}^{-}(\omega) + P_{\delta}^{+}(\omega) = \frac{1 + R(\omega)}{1 - V(\omega)R(\omega)} \quad (5)$$

The ‘soft source impedance’, which is a version of the input impedance that takes into account a less than perfect acoustic reflectance condition at the lips, can then be written as

$$Z_{\delta}(\omega) = Z_c \frac{1 + R(\omega)}{1 - V(\omega)R(\omega)}. \quad (6)$$

In this paper only measurements of the acoustic reflectance of artificial lips are presented. However, the wider theory that is concerned here, involving soft source impedance, is included for completeness.

## METHODS

### Wave separation apparatus for measurement of acoustic impedance and acoustic reflectance

#### Overview of the wave separation method

A series of experiments were conducted to measure the reflectance properties of a pair of *in vitro* artificial lips mounted onto a replica mouth cavity of adjustable volume. The primary

objective was to observe the variation in the reflectance properties of the lips (discussed in section 2.2) as a function of the internal water pressure in the lips, which is the main lip control parameter (see section 3.2 for details about the artificial lips). A secondary experiment was to record the lip reflectance behaviour as a function of the mouth cavity volume.

Reflectance measurements were obtained using the wave separation technique outlined by Kemp *et al*[2] and Kemp and Smith[9]. A brief summary of the method, which does not include full details of the essential calibration procedures, is presented here.

The wave separation method allows a frequency domain reflection function, and the linear acoustic impedance, to be obtained for any test object. The method employs a source tube with a pair (or multiple pairs) of microphones embedded in its walls. The source tube is coupled on one end to a loudspeaker, and on the other end to the measurement object. A schematic diagram and photograph of the wave separation apparatus is shown in Figure 1.

Wave separation uses the transfer functions between a pair of microphones, obtained during one or more loudspeaker sweep(s), in order to separate out the forward and backward going waves at the entrance plane of the measurement object. From these separated wave signals it is then possible to calculate the reflectance and linear and/or soft source acoustic impedance of the measurement object.

Consider any pair of microphones in the source tube,  $a$  and  $b$ , with  $b$  positioned further forward of  $a$  (i.e. further to the right in Figure 1). In the time domain, the transfer functions between microphones  $a$  and  $b$ , and between  $b$  and  $a$  may be written as

$$p_b^+ = p_a^+ \otimes h_{ab} \quad (7)$$

$$p_a^- = p_b^- \otimes h_{ba} \quad (8)$$

where  $\otimes$  denotes convolution, and  $p_b^+$  is the pressure of the forward going acoustic wave at microphone  $b$  (i.e. directed to the right in Figure 1), and so on.

Measurement of the acoustic pressures at microphones  $a$  and  $b$  leads, via a Z-domain transform and appropriate windowing, to a frequency domain expression for the transfer functions  $H_{ab}(\omega)$  and  $H_{ba}(\omega)$ . The frequency domain transfer functions can then be combined together to calculate the frequency domain reflectance function at the plane of microphone  $b$  as[2]

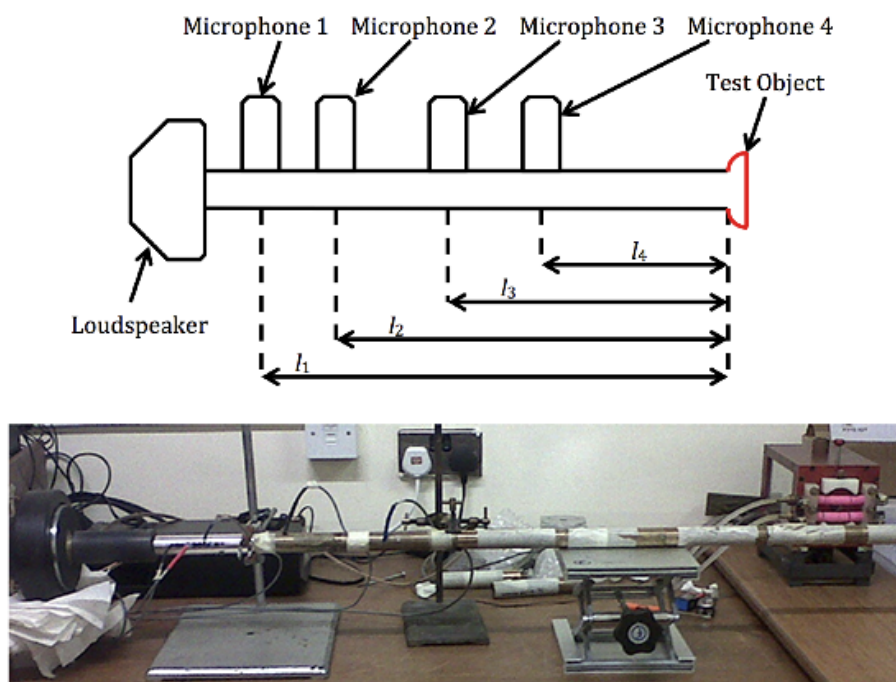
$$R_b(\omega) = \frac{H_{ab}(\omega) \cdot y(\omega) - 1}{H_{ab}(\omega) \cdot H_{ba}(\omega) - H_{ab}(\omega) \cdot y(\omega)} \quad (9)$$

where  $y(\omega) = \frac{P_a(\omega)}{P_b(\omega)}$ , and  $P_a(\omega)$  and  $P_b(\omega)$  are the frequency domain transforms of the recorded microphone signals.

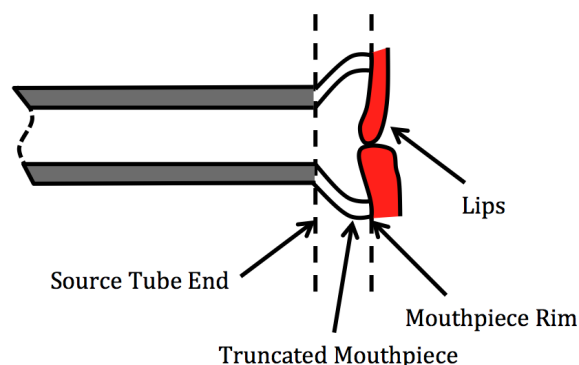
The use of more than a single pair of microphones in the source tube is to account for singularities which occur at frequencies that depend upon the microphone spacings. By employing four microphones, as in Figure 1, it is possible to combine reflectance calculations from multiple microphone pairings in order to obtain a smooth wideband measurement.

#### Projection of the reflectance function from microphone to measurement object

Equation 9 describes the frequency domain reflectance function  $R_b(\omega)$ , directed towards the measurement object, but as seen at the plane in line with microphone  $b$ . In the present study a pair of artificial lips formed the measurement object, so the reflectance measured at the plane of microphone  $b$  using equation 9 is thus termed  $R_b^{lips}(\omega)$ . However, in order to characterise the



**FIGURE 1:** A schematic and a photograph illustrating the layout of the wave separation apparatus. See section 3.1 for details on the use of the rig.

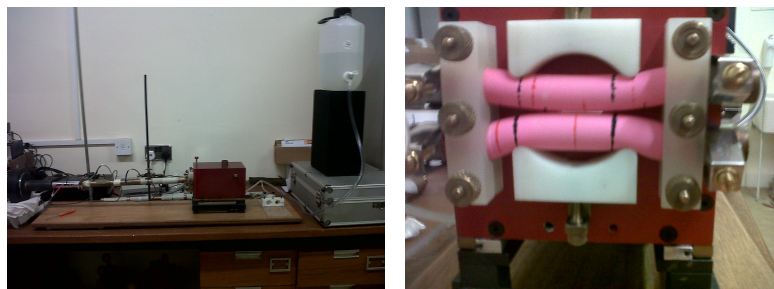


**FIGURE 2:** A schematic illustrating the coupler designed to allow the artificial lips to be seamlessly coupled to the measurement end of the wave separation apparatus's source tube.

reflectance of the artificial lips themselves, in isolation from the surrounding acoustic tube, the reflectance  $R_b^{lips}(\omega)$  must be 'projected' along the remainder of the source tube up to the plane at the face of the lips. This reflectance is called  $R^{lips}(\omega)$  and is the quantity sought in this work. Its calculation is now outlined.

A special coupler was designed that allowed a pair of artificial lips to be coupled to the source tube of the wave separation apparatus, as illustrated in Figure 2. A trumpet mouthpiece was machined to remove most of the throat, leaving just the rim and part of the cup. The diameter of the remaining cup was chosen to match the diameter of the source tube so that a suitably seamless join was possible.

The first step in the lip reflectance calculation was to obtain the frequency domain reflectance  $R_b^{lips}(\omega)$  at the plane of microphone  $b$ , using the inter-microphone transfer functions and equation 9. This reflectance was then projected along the source tube to produce a



**FIGURE 3:** Photographs showing the *in vitro* artificial lips that were the subject of the reflectance measurements. At left the artificial mouth/artificial lips device (red box) has been mounted onto the wave separation apparatus as described in section 3.1.

reflectance,  $R_{se}^{lips}(\omega)$ , as seen from the *end* of the source tube. This was achieved through use of a calibration reflectance  $R_b^{cap}(\omega)$  obtained from a hard, flat metal cap placed over the end of the source tube instead of the mouthpiece rim/artificial lips. The relevant calculation was obtained using

$$R_{se}^{lips}(\omega) = \frac{R_b^{lips}(\omega)}{R_b^{cap}(\omega)}. \quad (10)$$

The next step was to convert the reflectance at the end of the source tube,  $R_{se}^{lips}(\omega)$ , into a source tube admittance  $Y_{se}^{lips}(\omega)$ , which could be projected through the mouthpiece cup and up to the plane of the lips to produce a lip admittance  $Y^{lips}(\omega)$ . The reflectance of the lips themselves,  $R^{lips}(\omega)$ , was then computed using the relation

$$R^{lips}(\omega) = \frac{1 - Y^{lips}(\omega)Z_c}{1 + Y^{lips}(\omega)Z_c} \quad (11)$$

where the characteristic impedance  $Z_c$  has already been defined in equation 2. Thus the journey from the initial measurement of  $R_b^{lips}(\omega)$  to the calculation of  $R^{lips}(\omega)$  was completed.

### A controllable *in vitro* lip-reed model

The *in vitro* artificial lips used for the acoustic reflectance measurements were composed of a pair of water-filled latex balloons positioned over a 2.5cm diameter hole in a ‘mouth’ cavity of adjustable volume[5, 11]. The lip separation, internal water pressure, and volume of the mouth cavity were the three main control parameters. Photographs of the setup are shown in Figure 3.

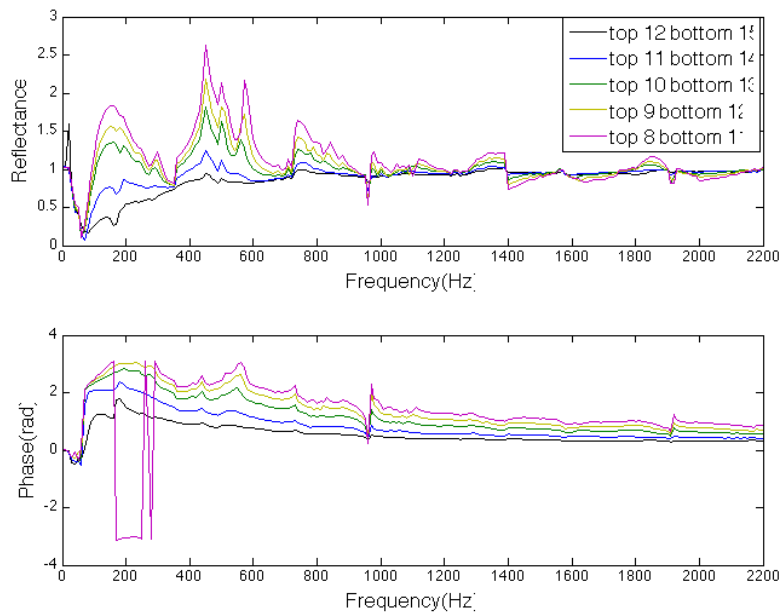
## RESULTS AND DISCUSSION

### Experimental measurements of the artificial lip-reed acoustical reflectance as a function of internal lip water pressure

#### Lip reflectance as a function of lip separation

The results in Figure 4 show the reflectance and phase when the lips of the artificial mouth were opened at different separations. The number of screw turns indicated relates to the positioning of the ‘artificial teeth’ that control the separation of the lips, as these are moved up and down on a pair of long screws. The number of turns indicated are relative to the rest position when the lips were just fully open. Before a measurement was made, the lips were set





**FIGURE 4:** Reflectance and phase of the artificial lips for constant internal lip pressure and varying lip separation, with a large back cavity volume.

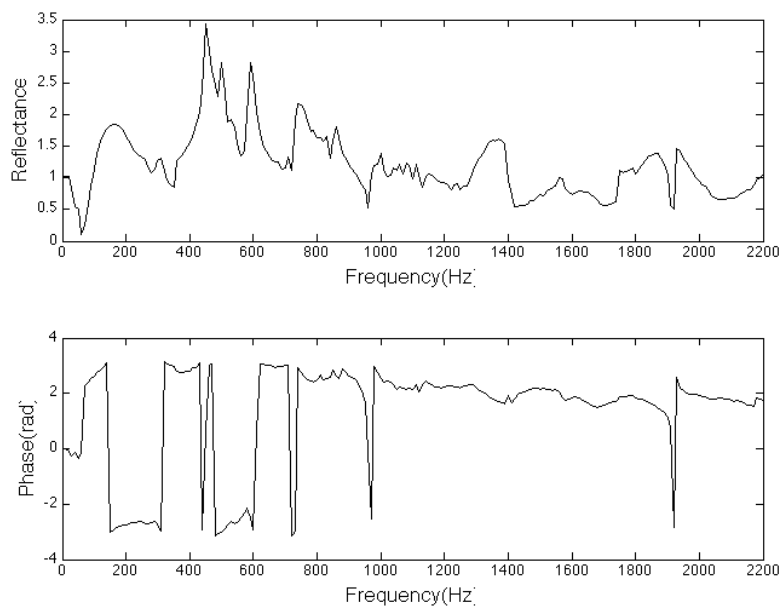
at the separation indicated by the number of screw turns, and then advanced into the mouthpiece so a seal was made. As the lips were pressed into the mouthpiece, they closed slightly and in the current set up the final separation could not be measured.

The two smallest lip separations in Figure 4, top 8/bottom 11 and top 9/bottom 12, show a pair reflectance minima below 200Hz that apparently correspond to frequencies absorbed by the lips. As the lips are opened, these minima are moved nearer to one and become local maxima which increase along with the other maxima seen around 500Hz. If the reflectance function goes above unity, as it soon does for the other lip separations shown, it is likely that the lips have opened to reveal an air gap.

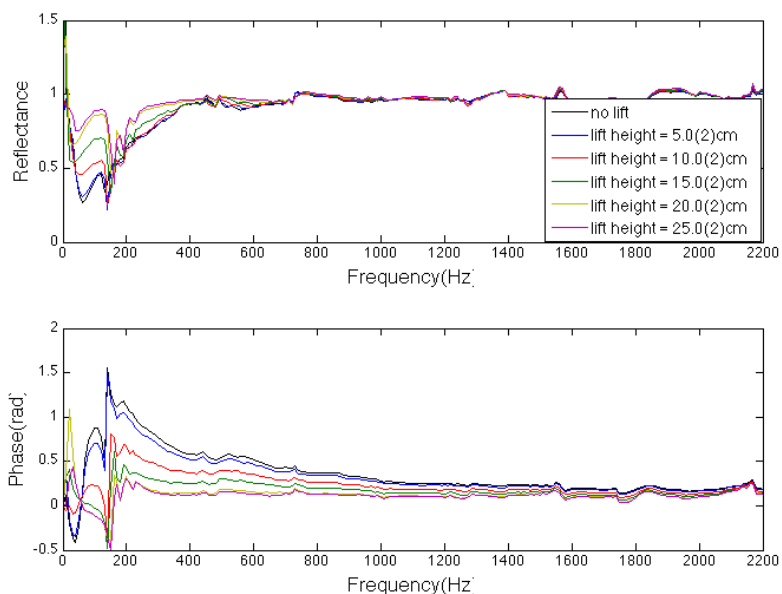
Figure 5 shows the reflectance and phase of the cavity behind the lips which was measured by sealing the mouthpiece with blue tac onto the lip housing with the lips removed. Comparing the reflectance of the largest three separations in Figure 4 with the reflectance in Figure 5 shows that at larger separations the reflectance properties of the system are dominated by the volume of air in the mouth cavity, which is to be expected.

#### Lip reflectance as a function of internal lip water pressure and mouth cavity volume

Measurements were made for different water reservoir heights ('lift elevations'), each of which corresponded to a different internal water pressure within the artificial lips. Figure 6 shows the reflectance and phase results for a number of different water reservoir heights. Above 400Hz the reflectance is close to 1 for all lift elevations which corresponds to frequencies being fully reflected. Below 400Hz there are a series of reflectance minima where acoustic frequencies are absorbed, indicating deviation from the typical assumption of perfect reflectance across all frequencies. The strongest of these reflectance minima seem to be around 150Hz and 190Hz, and presumably originate from the principal natural resonance frequencies of the two artificial lips. Such a result clearly demonstrates the 'softness' of the lip-reed at these frequencies, and the fact that in a playing configuration energy will be drawn away from the acoustic standing



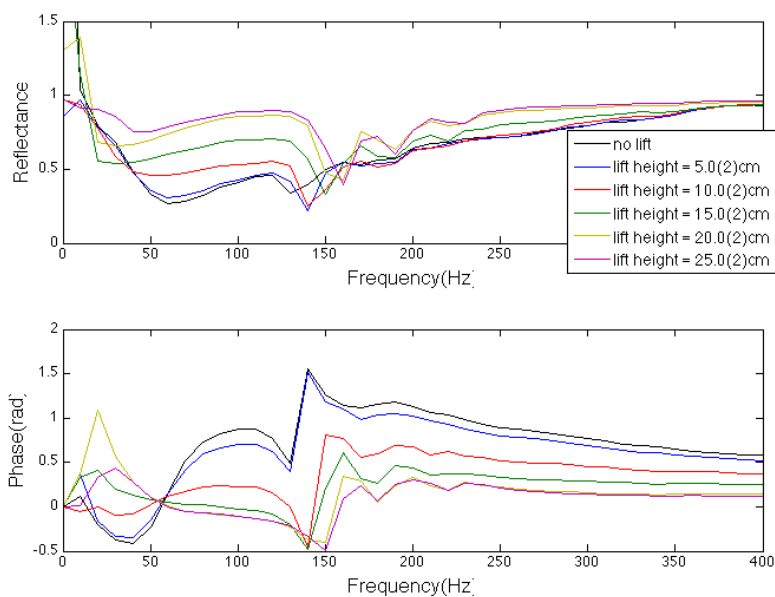
**FIGURE 5:** Reflectance and phase of the mouth cavity in isolation (artificial lips removed completely), when configured to have a small volume. This is essentially a measurement of the reflectance of the small mouth cavity itself, for comparison with the reflectances when the artificial lips are used to 'seal off' the cavity.



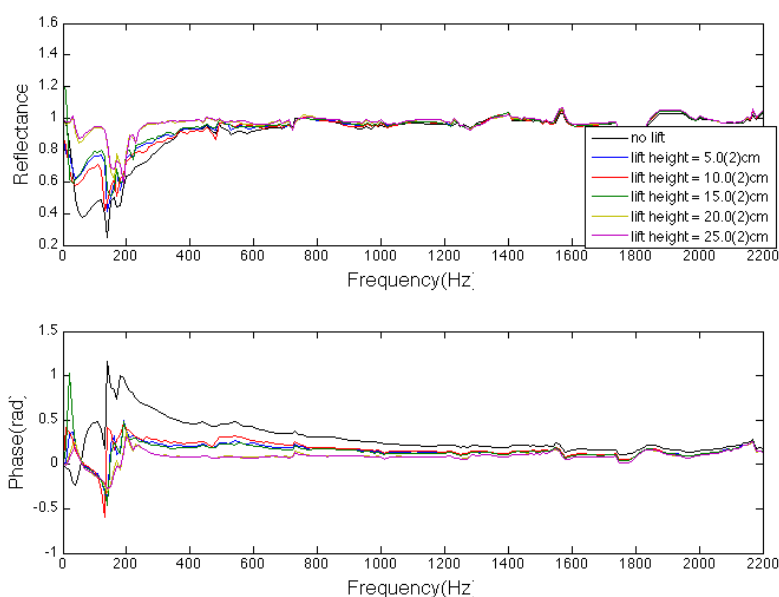
**FIGURE 6:** Reflectance and phase of the artificial lips when mounted onto a mouth cavity with large volume, as a function of internal water pressure in the lips. The highest water pressure corresponds to the largest lift height, 25cm in this example.

wave simply because of the mechanical deformation of the lips.

Figure 7 is a magnified view of the reflectance minima seen in Figure 6. The position of the second minima is shown to increase with water height, with a 30Hz increase in frequency over a 25cm change in the height of the water column. Conversely, the position of the first minima



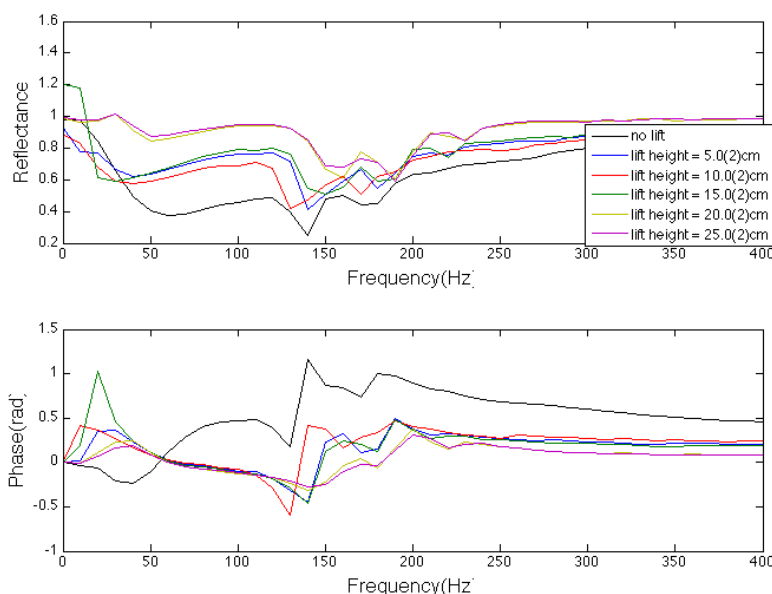
**FIGURE 7:** A low frequency close up of Figure 6 highlighting the change in reflectance notches seen as the internal water pressure in the artificial lips is changed.



**FIGURE 8:** Reflectance and phase of the artificial lips when mounted onto a mouth cavity with large volume, as a function of internal water pressure in the lips. The highest water pressure corresponds to the largest lift height, 25cm in this example.

decreases by 40Hz over the first 15cm of water column elevation, and then increases by 20Hz over the final 10cm. There is also a general shift of reflectance nearer to a value of 1 as the water height increases as the lips become stiffer and reflect more of the incident wave.

Figure 8 shows the same experiment with a smaller mouth volume behind the lips. The volume of air behind the lips could be sectioned off by lowering a plate which left a very small



**FIGURE 9:** A low frequency close up of Figure 8 highlighting the change in reflectance notches seen as the internal water pressure in the artificial lips is changed.

volume of air behind the lips. Again for frequencies above 400Hz the reflectance is close to 1. Figure 9 shows the magnified results for the small back cavity. The results are quite similar to those obtained from the large cavity, with the position of the second minima increasing with water height and the position of the first minima decreasing and then increasing as the water is elevated. This suggests that when the lips are in a closed configuration, the reflecting properties of the system are dominated by the lips and not the volume of air behind them. This clearly contrasts with the open configuration discussed in section 4.1.1.

## CONCLUSIONS

This paper has continued on from the work of Kemp and Smith[9] to include some systematic measurements of lip reflectance using wave separation apparatus and a pair of *in vitro* artificial lips. Notches in the lip reflectance function, corresponding to a deviation of the lip surface reflectance from the generally assumed unitary reflectance, were observed between 150-190Hz, with the precise frequency determined by the internal water pressure in the lips. Higher water pressures led to higher notch frequencies, which is to be expected. Ongoing work will further quantify these various effects, and seek to incorporate them into a working computational model of the lip-reed mechanism.

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